

## COASTAL INLETS OF TEXAS, USA

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**Abstract:** Presently, 16-17 permanent inlets connect the inland coastal waterways and rivers to the Gulf of Mexico on the 560-km long coast of Texas. Processes controlling inlet stability in Texas are typically more complex than those acting on the Atlantic and Pacific Ocean coasts of the United States, where the astronomical tide dominates. The tide on the Texas coast is predominantly or fully diurnal and with small range; however, the large surface areas of most Texas bays produce large tidal prisms. Wind is strong throughout the year, either from the southeast in summer or as episodic northeasterly fronts in autumn and winter. Non-astronomical seasonal variations in water level are comparable to the tidal range of Texas bays. Creation of inlets on the Texas coast is ongoing for environmental, commercial, and recreational reasons, and this paper discusses the status and challenges posed to inlet creation, stability, and maintenance.

### INTRODUCTION

The coast of Texas is approximately 560 km long and is fronted by sandy barrier islands or barrier spits (Fig. 1) with the exceptions of about 50 km each of mainland near Sabine Pass and Freeport. Texas inlets to the Gulf of Mexico originate as natural river mouths, relocated river mouths, natural entrances to bays, and artificial cuts through the barriers. There are eight federal channels: Sabine Pass, Galveston Pass, Freeport Ship Channel, Mouth of Colorado River Navigation Channel, Matagorda Ship Channel, Aransas Pass, Mansfield Pass, and the Brazos-Santiago Pass. The Mouth of Colorado River and Mansfield Pass are shallow draft (at about 4-m depth), and the other six are deep draft at 13-m depth or greater. Permanent inlets of Texas are listed in Table 1, according to origin. Many inlets in Texas are named either as “passes” or as “cuts,” signifying the action of a hurricane or of human intervention in opening them. At the time of this

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14. ABSTRACT <b>Presently, 16-17 permanent inlets connect the inland coastal waterways and rivers to the Gulf of Mexico on the 560-km long coast of Texas. Processes controlling inlet stability in Texas are typically more complex than those acting on the Atlantic and Pacific Ocean coasts of the United States, where the astronomical tide dominates. The tide on the Texas coast is predominantly or fully diurnal and with small range; however, the large surface areas of most Texas bays produce large tidal prisms. Wind is strong throughout the year, either from the southeast in summer or as episodic northeasterly fronts in autumn and winter. Non-astronomical seasonal variations in water level are comparable to the tidal range of Texas bays. Creation of inlets on the Texas coast is ongoing for environmental commercial, and recreational reasons, and this paper discusses the status and challenges posed to inlet creation, stability, and maintenance.</b>					
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writing, January 2007, 17 inlets along the Texas coast were open to the Gulf of Mexico. Many inlets of Texas are described by U.S. Army Corps of Engineers ((USACE) 1992), and Morton (1977) studied morphologic response to seven federal Texas inlets with jetties (Mouth of Colorado River had not yet been opened).

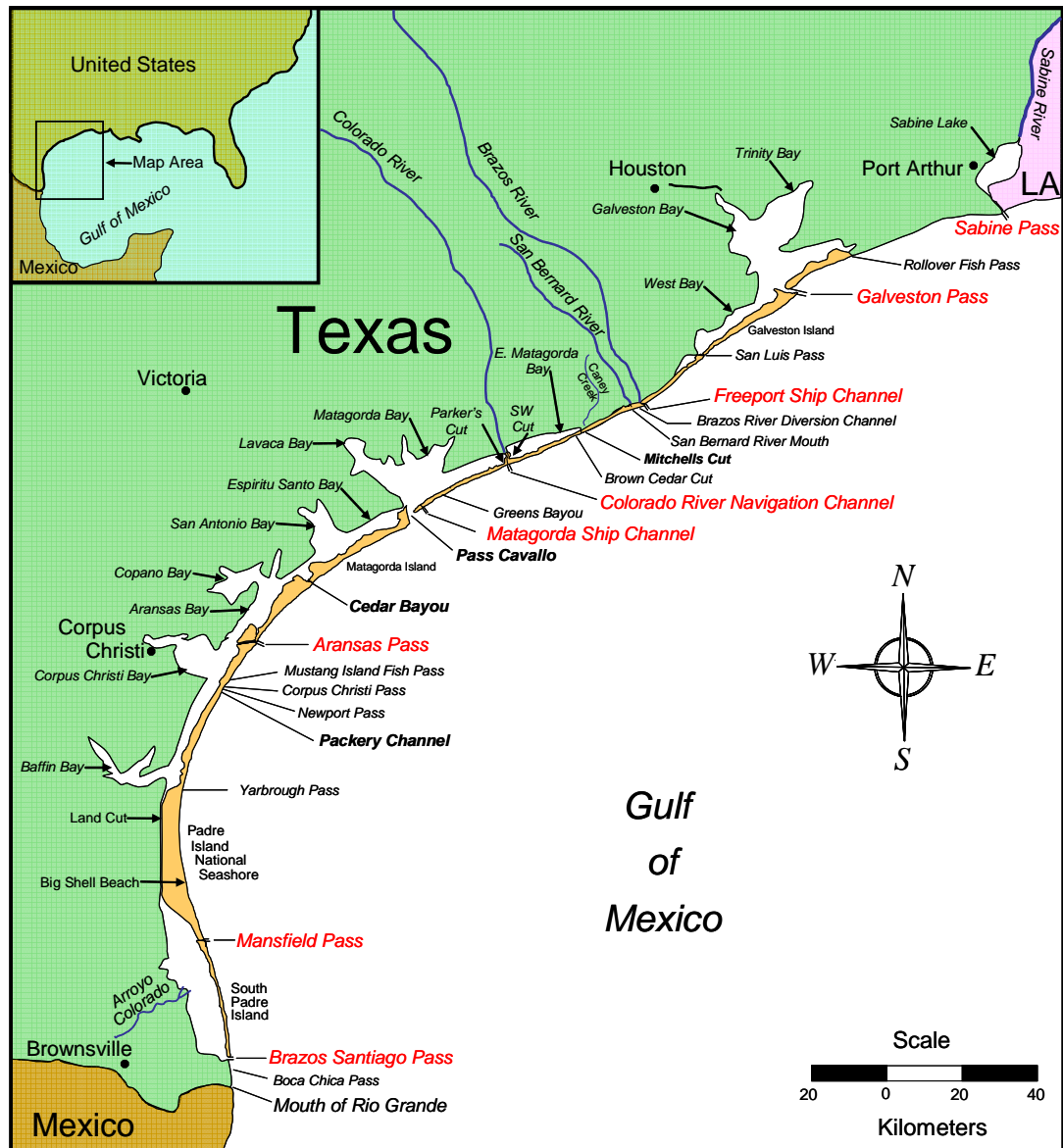


Fig. 1. Location map for Texas coast with presently open and other inlets

The need for additional inlets along the Texas coast, in particular, for small inlets to allow exchange of water with the Gulf of Mexico and inland bays and lagoons, locally called “fish passes,” was documented by Carothers and Innis (1960). In the mid 20<sup>th</sup> Century, two major inlets with jetties were constructed, Mansfield Pass (Hansen 1960; Kieslich 1977) and the Matagorda Ship Channel (Kraus et al. 2006). Some fish passes have been successful such as Rollover Pass opened to upper Galveston Bay opened in 1959 (Bales and Holley 1989) and Mitchells Cut opened to East Matagorda Bay in 1989

as a flood-relief channel (USACE 1992). Other inlets such as Yarbrough Pass to Baffin Bay (Lockwood & Andrews 1952), most recently cut in 1952, and the Mustang Island Fish Pass opened in 1972 (Behrens 1979) have been unsuccessful by rapidly shoaling and closing. In contrast, Rollover Pass expanded greatly from its planned dimensions (because of a large phase difference between the Gulf and upper Galveston Bay) and had to be controlled by revetments and a channel weir. Other inlets located close to the Gulf have been considered for opening, including re-opening Parkers Cut to connect Matagorda Bay to the Colorado River Navigation Channel, and opening of a “Southwest Corner Cut” to connect East Matagorda Bay to the Colorado River Navigation Channel (Kraus and Militello 1999). Environmental and legal issues have reduced agency enthusiasm for opening fish passes, but inlet creation continues, as demonstrated by opening of Packery Channel in 2005 (Kraus and Heilman 1997; Williams et al. 2007) and interest in maintaining the long-lived ephemeral inlet Cedar Bayou Pass connecting the Gulf to Mesquite Bay (Simmons and Hoese 1959; Shepsis and Carter 2007). Concern has also been expressed by local interests in maintaining the San Bernard River Mouth (Lin et al. 2003).

**Table 1. Coastal Inlets of Texas to Gulf of Mexico**

Origin	Name	Comments
<b>Inlets Open as of January 2007</b>		
River Mouths	Sabine, Brazos, San Bernard, Colorado, Rio Grande	The modern Colorado River Mouth diverted into Matagorda Bay in 1992. Brazos River mouth relocated south of Freeport Ship Channel (original mouth) in 1929.
Natural Exchange Passes	Galveston, San Luis, Pass Cavallo, Cedar Bayou, Aransas, Brazos Santiago	Cedar Bayou is a long-lived ephemeral inlet to San Antonio Bay & Aransas Bay.
Artificial Inlets (Engineered Cuts)	Rollover Pass, Freeport Ship Channel, Mitchell's Cut, Matagorda Ship Channel, Packery Channel, Mansfield Pass	
<b>Selected Ephemeral Inlets and Hurricane Passes</b>		
Connecting to Gulf	Brown Cedar Cut & Greens Bayou; Corpus Christi Pass and Newport Pass	Likely will not open again because other inlets present
Proposed Passes to Rivers	SW Corner Cut to connect East Matagorda Bay and Colorado River Navigation Channel	Active discussion on opening this inlet
<b>Attempted, but Failed Artificial Inlets</b>		
Artificial Inlets	Mustang Island Fish Pass to Corpus Christi Bay; Yarbrough Pass to Baffin Bay	Both closed or became inefficient in short time.

Although Carothers and Innes (1960) provide design guidance for constructing fish passes along the Texas coast, it appears that an update based on more recent experiences and knowledge of Texas inlet processes would be beneficial to the coastal engineering

and science communities. Creation of inlets can cause morphologic change on widely varying space and time scales (Kraus 2006). It is the intent here to document recent observations and experiences with inlets along the Texas coast, updating the literature.

## **STABILITY OF TEXAS COASTAL INLETS**

Many natural processes control the creation, stability, and navigability of coastal inlets. Main factors are:

1. Longshore sediment transport, including wind-blown transport.
2. Astronomical tide.
3. Wind tide.
4. Seasonal change in water level.
5. Regional precipitation and watershed characteristics.
6. River discharges for those inlets connected to rivers.
7. Sediment grain size and geological environment.
8. Human interventions, principally dredging, but also constriction of inlet width by jetties and reduction of longshore sediment transport reaching the inlet.
9. Hurricanes and tropical storms.
10. Relative sea-level rise.
11. Width to depth ratio of inlet channel with jetties, with smaller ratio providing a more hydraulically efficient channel (e.g., Kraus and Heilman 1997).

In this paper, the wind tide is examined, as its action is more regular and much more pronounced than along other coasts of the United States and dominates extreme water levels and currents at Texas coastal inlets. Relative sea-level rise (RSLR) on the Texas coast varies from about 3 mm/year at the Port Isabel (Brownsville) tide gauge to greater than 10 mm/year at Freeport and Galveston. RSLR may increase bay and lagoon surface area, hence tidal prism, and promote inlet stability. On the other hand, protective jetties will become lower with respect to the water surface, allowing more littoral sediment to enter the entrance channels they protect. The sediment along the Texas coast is predominantly fine quartz sand with median grain size of 0.16-0.18 mm.

Because of the concave curvature of the Texas coast to the southeast, regional longshore sand transport is directed from north to south from Sabine Pass and from south to north from the Rio Grande to converge along central Padre Island (Carothers and Innis 1960; Watson 1971). Of course, there are local reversals, especially at inlets (e.g., Heilman and Edge 1996). Owing to the coastal curvature, widely varying magnitudes of net and gross longshore sand transport rates are expected. Volumes of sand dredged from inlet entrance channels indicate average rates of 100,000-300,000 m<sup>3</sup>/year, but can reach 500,000 m<sup>3</sup>/year.

Wind blowing from the Gulf of Mexico and surge by tropical storms elevate water at the shore, promoting longshore transport in the swash zone. Swash zone transport can cause spit growth into inlets without structures and sand back-passing (sand moving around landward side of a jetty) with spit growth for inlets with low jetties (Fig. 2). The longshore component of wind can also be strong, moving sand over portions of jetties

located on the dry beach and contributing to shoal growth and channel infilling (Fig. 3). Intrusion of channels by wind-blown sand can figure prominently in the closure of small inlets along the Texas coast (Kraus and Heilman 1997).

Hurricanes open many short-term and sometimes long-term ephemeral inlets in the Texas barrier islands (Hayes 1965). Examples of longer term ephemeral inlets are Cedar Bayou opening to Aransas Bay and San Antonio Bay through Mesquite Bay (Simmons and Hoese 1959; Shepsis and Carter 2007), and the presently closed Brown Cedar Cut at the eastern end of East Matagorda Bay (Mason and Sorenson 1971). Brown Cedar Cut will likely remain closed owing to artificial opening of nearby Mitchells Cut in 1989.



Fig. 2. Mouth of Colorado River, showing sand spit growing into channel from east (right) by transport landward of weir jetty, Jul 06



Fig. 3. Packery Channel with wind-blown sand covering the south (lower) jetty, Aug 06

Astronomical tide along the Texas coast is predominantly diurnal from Galveston to Sabine and fully diurnal from about Matagorda Bay to the Rio Grande. Gulf of Mexico tide range on this coast is on order of 0.6 m. Astronomical tide in the bays and lagoons is diurnal, and its range is considerably less than that of the open coast. Some large water bodies, such as Baffin Bay, are considered non-tidal by the National Ocean Service (tide range less than about 0.05 m), and others such as at Port Mansfield are marginally tidal.

In the bays and Texas along the coast, water level extremes and currents through inlets are controlled more by wind and seasonal variations than by astronomical tide. For example, Kraus and Militello (1999) report water level at two stations at the eastern (EMAT) and southwestern (SWEMAT) ends of the major axis of East Matagorda Bay from 7 Sep 1995 to 8 Feb 1996 relative to Mean Lower Low Water (MLLW) (Fig. 4). The astronomical tide range in this bay is 0.1 m. The measurements show an almost 0.6-m tilt in water level over the 32 km between gauges during one strong northeast front with wind speed of 12 m/s, with a 0.2 to 0.3-m tilt being common during frontal passages. The bay is 37 km long, and typical depths are in the range of 0.6 to 1.2 m.

On the Texas coast, seasonal highs occur around May and October, and seasonal lows occur around August and December-January (Fig. 5). The seasonal range is about 0.2-0.3 m, which is comparable to or exceeds the tide range in many Texas bays and lagoons. Figure 5 plots monthly water level for open coast tide gauges (Galveston, Bob Hall Pier at Corpus Christi; and bay gauges (Rawlings at Mouth of Colorado River; Lavaca, and Port Isabel in the lower Laguna Madre) for year 1999. Barge operators and others involved with inlet and coastal waterway navigation are aware of the seasonal highs and lows, and their possible benefit or impediment, respectively, to vessel transit.

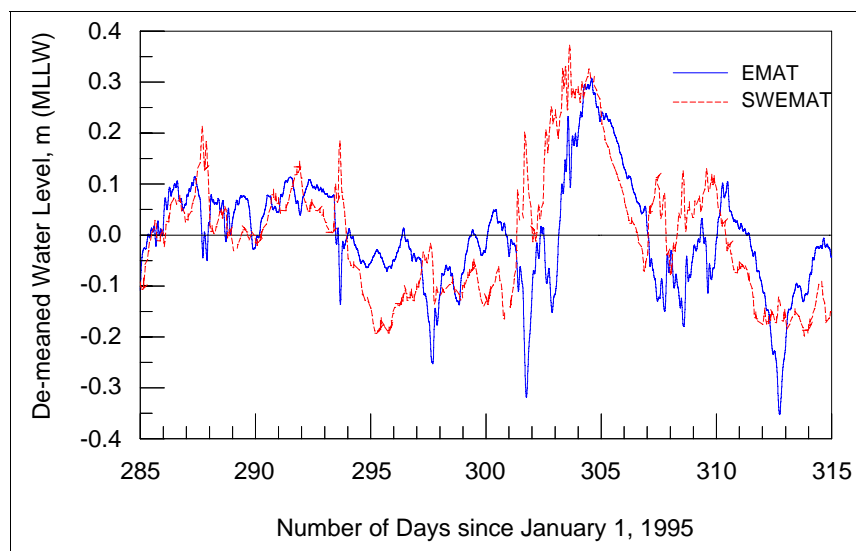


Fig. 4. Demeaned water levels at two stations in East Matagorda Bay

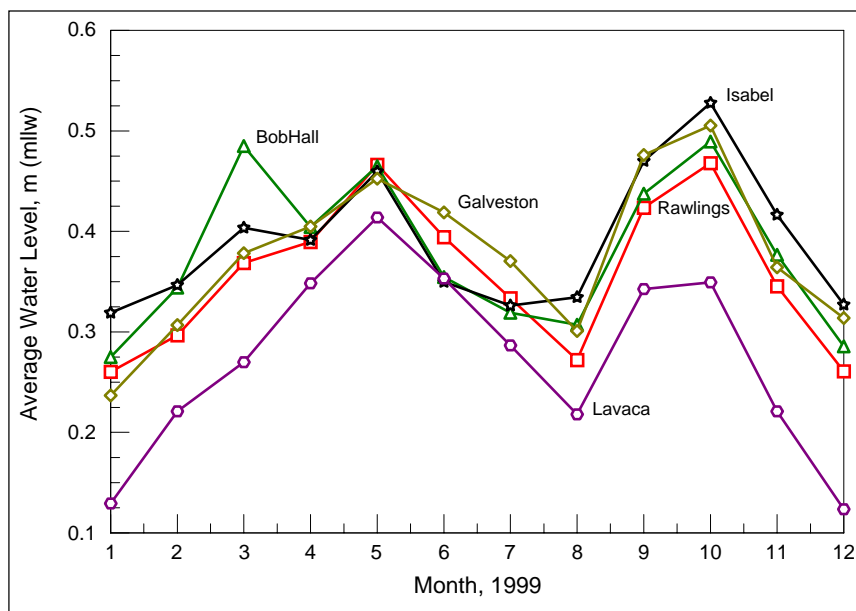


Fig. 5. Example of seasonal change in water level along the Texas coast

Strong wind from the north or northeast can overcome the astronomical tide in forcing water through Texas inlets, as shown in Fig. 6, based on measurements of the current,

water level, and sustained wind from north at Packery Channel (Williams et al. 2007). Behrens (1979) explains how the strong wind from the southeast can enhance the flood current through inlets and strong wind from the north or northeast can enhance the ebb current. For such reasons, Price (1952) noted that funnel-shaped inlets in the southwest corners of bays on the upper Texas coast or in the southeast corners of bays on the lower Texas coast tend to be the natural and stable inlets to the bays. Pass Cavallo in Matagorda Bay is such a southwest corner inlet, remaining open despite capture of much of the tidal prism by cutting of the Matagorda Ship Channel in 1966 (Kraus et al. 2006; Batten et al. 2007). Because wind tide and seasonal lows can dominate astronomical tide, the USACE Galveston District has defined a navigation datum called Mean Low Tide that is specific to location and lies below MLLW (Kraus et al. 1997). Seasonal lows in water level make marginally stable small inlets prone to closure.

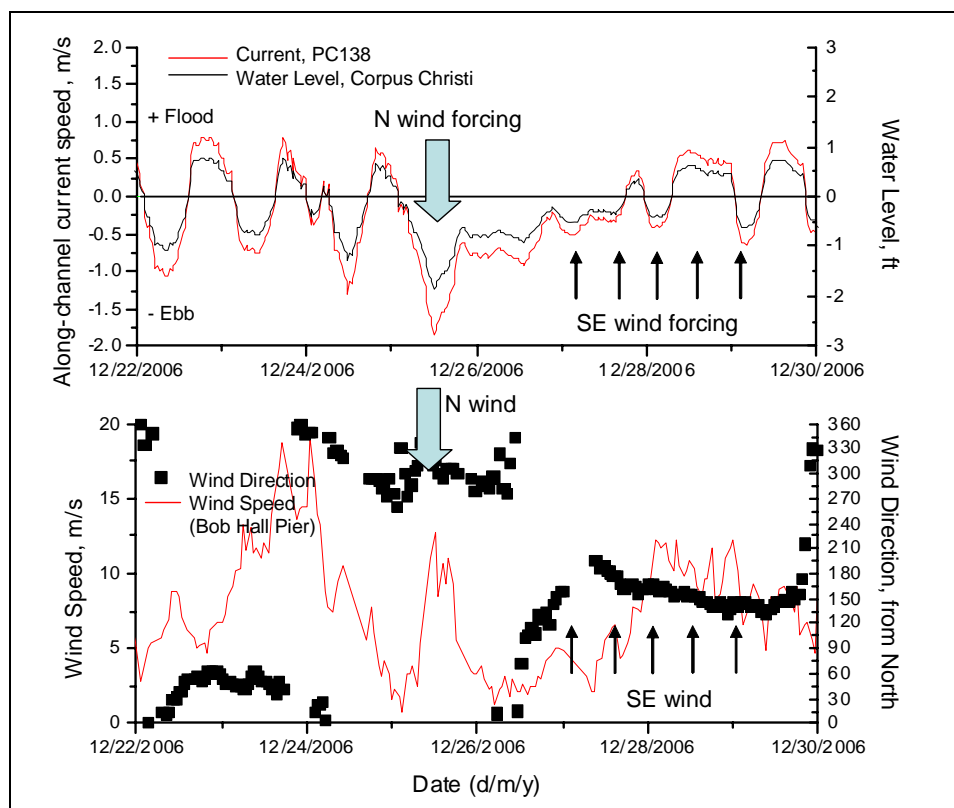


Fig. 6. Response of current to wind forcing, Packery Channel, Texas (from Williams et al. 2007)

## TEXAS INLET STABILITY

### Implications of Diurnal Tide

It is empirically known that a cross-sectionally stable inlet located on a sandy coast tends to have a mean-maximum velocity through it of approximately 1 m/s (Escoffier 1940; Bruun 1968). By “mean-maximum velocity” is meant the average of a regularly occurring maximum velocity, such as would occur on spring tide. If it is assumed that the discharge is solely related to the tidal prism and that there is a sinusoidal tide with one component, the maximum discharge  $D_m$  and tidal prism  $P$  can be related as:



$$P = \int_0^{T/2} D_m \sin\left(\frac{2\pi}{T}t\right) dt \quad (1)$$

where  $T$  is the tidal period, and  $t$  is time. The integration yields:

$$D_m = \frac{\pi}{T} P \quad (2)$$

Tidal prism is defined as the volume of water exchanged between an estuary or lagoon and the open sea during one tidal period (between high to low tide in the bay, giving an ebb-tidal prism, or between low to high tide in the bay, giving a flood-tidal prism). Therefore, the integration limit in Eq. 1 is taken to be  $T/2$ . Tidal prism can also be calculated as the product of the effective bay surface area served by the subject inlet times the tidal range, or from a computation of water discharge, as through a numerical model. By definition of a discharge, the mean-maximum velocity  $V_{mm}$  is:

$$V_{mm} = \frac{D_m}{A_C} \quad (3)$$

in which  $A_C$  is the minimum inlet channel cross-sectional area at mean sea level (msl).

Although refinements have been made in empirical predictive equations relating  $A_C$  and  $P$ , it is convenient for present discussion to consider the linear relation found by O'Brien (1969), based in part on analysis of inlets without jetties:

$$A_C = C P \quad (4)$$

where  $A_C$  is expressed in  $m^2$ ,  $P$  is expressed in  $m^3$ , and  $C = 6.6 \times 10^{-5}$  with units  $m^{-1}$ . The original units of this equation in feet were converted to metric units for the present work. Kraus (1998) derived a form of Eq. 4 by consideration of a balance of sand transport by the inlet channel-clearing current and the channel infilling by the longshore transport. This equation was also expressed directly in terms of water discharge through the inlet, in addition to tidal prism.

Substitution of Eq. 2 and Eq. 4 into Eq. 3 gives (O'Brien 1969):

$$V_{mm} = \frac{\pi}{CT} \quad (5)$$

For a semi-diurnal inlet,  $T = 12$  hr, 25 min = 44,712 s. Then, Eq. 5 yields  $V_{mm} = 1.06$  m/s, in agreement with empirical observations. For a tide that is primarily diurnal, the tidal period is 89,424 s, giving  $V_{mm} = 0.53$  m/s. The conclusion is that an inlet in a diurnal tidal setting may require a smaller mean-maximum tidal velocity to maintain channel cross-sectional area stability as compared to inlets in a semi-diurnal setting, the more common type of inlet. The Texas coast is an ideal site to explore such a possibility, although the wind tide is expected to take as much a role as the astronomical tide in controlling stability of inlets on the Texas coast.

### Implications of Wind Tide – Simple Model for Multiple Tidal Inlets

In this section, the consequence to the current of a wind tide is explored with a simple mathematical model of a bay with two inlets, and model parameters correspond to a bay similar to East Matagorda Bay. The model is a slight extension of a Keulegan bay approach as discussed in Chapter 13 of Dean and Dalrymple (2002). Following their notation, we define:

$$F = K_{en} + K_{ex} + \frac{f L}{4R_H} \quad (6)$$

where  $K_{en}$  and  $K_{ex}$  = inlet entrance and exit loss coefficients (typically specified as 0.3 and 1.0, respectively),  $f$  = Darcy-Weisbach friction coefficient,  $L$  = effective length of inlet, and  $R_H$  = hydraulic radius of a rectangular cross-section inlet of depth  $h$ . Then, the equations of motion are, for two inlets serving the same bay:

$$\frac{dU_i}{dt} = -\frac{g}{L_i} (\eta_B - \eta_o \pm \delta) - \frac{F_i}{2 L_i} |U_i| U_i \quad (7)$$

and

$$\frac{d\eta_B}{dt} = \frac{1}{A_B} (A_{C1} U_1 + A_{C2} U_2) + \frac{D}{A_B} \quad (8)$$

where  $U_i$  = velocity of inlet  $i = 1$  or  $2$ ,  $t$  = time,  $g$  = acceleration of gravity ( $9.8 \text{ m/s}^2$ ),  $\eta_B$  = water-surface elevation of bay,  $\eta_o$  = water surface elevation of ocean (Gulf of Mexico in this paper),  $\delta$  = tilt in water surface elevation across a bay as caused by wind,  $A_C$  = inlet cross-sectional area below mean sea level,  $A_B$  = surface area of bay, and  $D$  = discharge into the bay, as from a river.  $D$  was set to zero in this paper. The inlets are assumed to be located at the opposite ends of the bay, and the water level in the entire bay responds to each inlet. Other assumptions of a Keulegan bay apply.

The model formulation is similar to that of Seelig and Sorensen (1978), who included advective acceleration, omitted here, but did not include wind forcing. In a process-based model, the change in elevation by wind and associated current can be calculated by applying wind shear to the water surface, such as done for East Matagorda Bay by Kraus and Militello (1999) and described analytically by Kraus and Militello (2001), demonstrating that the tilt in water surface by wind blowing on a shallow bay is almost linear. The water surface responds rapidly to wind shear, and Kraus and Militello (1999) found it necessary to force the hydrodynamic model with 6-min averages of wind speed rather than 1-hr averages to obtain best agreement of the calculated water level and current with measurements. Here, the quantity  $\delta$  describes the tilt directly and must be specified. A Matlab program was written to solve Eq. 7 and Eq. 8 in time-marching manner, and the results were checked against the Keulegan (1967) solution that neglects the acceleration term in Eq. 7 and water surface tilt.

The above simple model for a dual-inlet bay system was operated to explore the action of strong wind on a dual inlet. The example here pertains to a bay with surface area of

$2 \times 10^8 \text{ m}^2$ ; primary inlet (denoted by subscript 1) of depth 3 m, width 300 m, and length 1,600 m; secondary inlet (denoted by subscript 2) on other side of bay of depth 1 m, width 50 m, and length 1,000 m; ocean forcing amplitude of 0.3 m (corresponding to a tidal range of 0.6 m) and sinusoidal diurnal tidal period of 89,424 s; and friction coefficient  $f = 0.06$ . This arrangement roughly describes East Matagorda Bay, with the primary inlet being Mitchells Cut and the secondary inlet being the proposed SW Corner Cut as a narrow, shallow channel through marsh. The cross-sectional area of Inlet 1 is 18 times larger than that of Inlet 2, so the discharge is correspondingly larger.

The situation calculated with only tidal amplitude forcing is shown in Figs. 7 and 8. The figures are plotted for a time interval past the ramp of the solution and cover one diurnal tidal period starting with phase 0 for the Gulf water level forcing. Due to relatively strong friction in long and shallow inlets, the water level in the bay lags the Gulf of Mexico water level substantially and is greatly reduced in range. The current velocity is greater in Inlet 1, as expected, because of its greater depth. Although the tidal forcing is sinusoidal, the non-linear friction terms in Eq. 7 distorts the inlet current velocity. Positive directed current denotes flood, and negative denotes ebb.

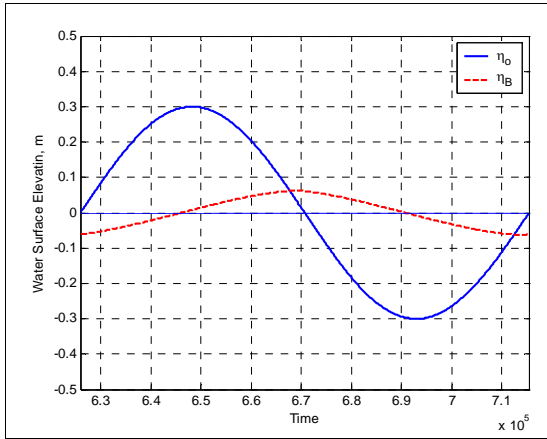


Fig. 7. Water level in Gulf and bay, no wind

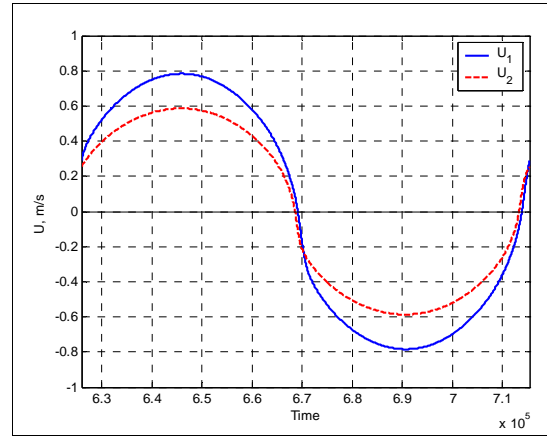


Fig. 8. Current in Inlet 1 and Inlet 2, no wind

The solution for a strong wind blowing such that the water surface is tilted upward 0.2 m toward Inlet 2 and downward 0.2 m at Inlet 1 is summarized in Figs. 9 and 10. In this situation, water can flow from the Gulf through the more efficient Inlet 1 of larger cross-sectional channel area, raising water level in the bay. The current through Inlet 2 increases greatly toward ebb, with the tidal flood current shown in Fig. 8 overcome by the wind tide to cause variable, but complete ebb flow through the tidal period (Fig. 10). The ebb current through the larger Inlet 1 is slightly reduced. The current through Inlet 2 is more distorted, with a longer duration during the latter portion of the tidal cycle.

The solution for a strong wind blowing such that the water surface is tilted upward 0.2 m toward Inlet 1 and downward 0.2 m at Inlet 2 is summarized in Figs. 11 and 12. In this situation, water can flow out of the bay and into the Gulf through the more efficient Inlet 1, lowering water level in the bay. The current through Inlet 2 increases greatly toward flood, with the tidal flood current shown in Fig. 8 overcome by the wind tide to

cause variable, but complete flood flow through the tidal period (Fig. 12). The flood current through larger Inlet 1 is slightly reduced. The current through Inlet 2 is more distorted, with a longer duration during the initial portion of the tidal cycle.

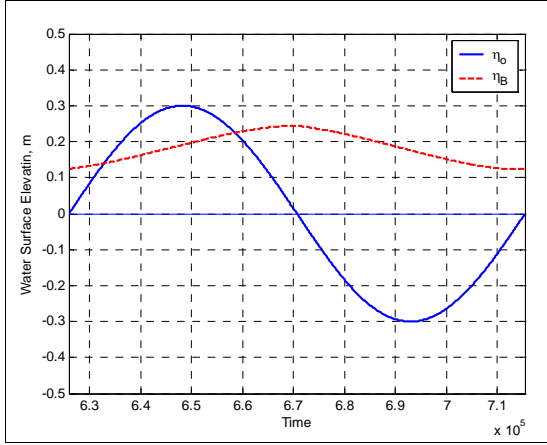


Fig. 9. Water level in Gulf and bay, water surface tilted upward toward Inlet 2

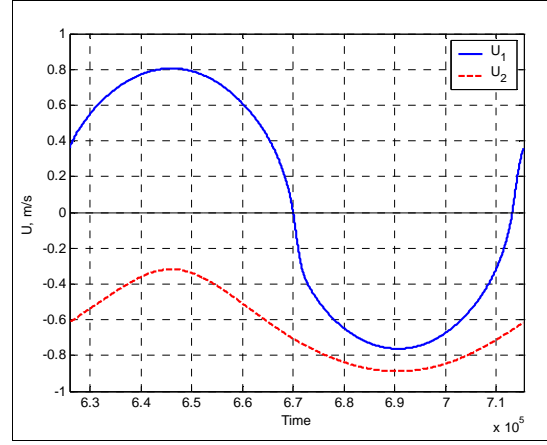


Fig. 10. Current in inlet 1 and Inlet 2, water surface tilted upward toward inlet 2

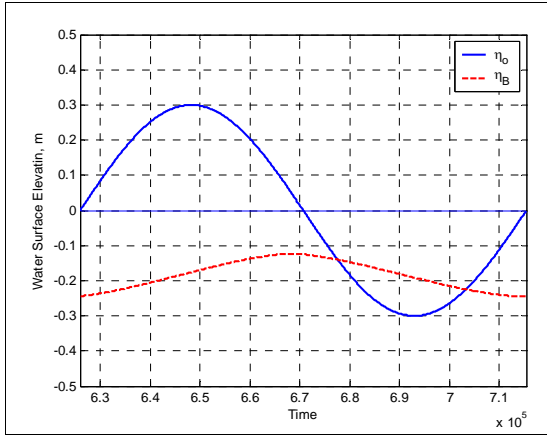


Fig. 11. Water level in Gulf and bay, water surface tilted upward toward Inlet 1

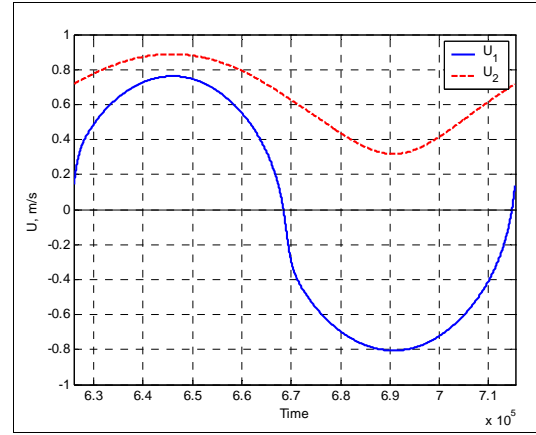


Fig. 12. Current in inlet 1 and Inlet 2, water surface tilted upward toward Inlet 1

## CONCLUDING DISCUSSION

As is known to coastal engineers and scientists working along the Texas coast, as well as to ship pilots, barge operators, and fishing boat operators who transit its inlets and inland coastal waters, the water level in bays and current velocity through Texas coastal inlets are strongly influenced by wind and seasonal change in Gulf of Mexico water level. Both wind tide and seasonal change in water level can exceed astronomical tide range in Texas bays and lagoons. As a result, stability of Texas inlets is strongly controlled by wind. Because the wind tide can control the magnitude of the ebb (or flood) current, inlet area-tidal prism relations alone should be applied with caution. In a future paper, the author plans to introduce a formalism that accounts for wind tide in inlet stability analysis.

Intrusion of wind-blown sand into inlet channels is another and significant factor controlling stability of smaller inlets in Texas. The situation of the Colorado River Mouth (Fig. 2) demonstrates that longshore sand transport in the swash zone and wind-blown sand can greatly constrict an inlet channel.

Finally, the diurnal tide experienced on the Texas coast suggests that a smaller maximum current may be sufficient to maintain stability as compared to the more common semi-diurnal inlet. This potential behavior, together with wind tide, acts in favor of inlet stability on the Texas coast. At present, numerical modeling technology allows accurate representation of inlet hydrodynamics involving all water forcing, multiple inlets to the bays, rivers, and inter-bay connecting waterways, as has been demonstrated for the Texas coast (Brown et al. 2003). The challenge remaining is to reliably estimate sediment transport and morphology change at coastal inlets.

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